Nanostructured Materials Produced by Severe Plastic Deformation

Hein Peter Stüwe

Erich Schmid Institute of Materials Science, Austrian Academy of Sciences and Institute of Metal Physics, University Leoben, Austria

e-mail: stuewe@unileoben.ac.at

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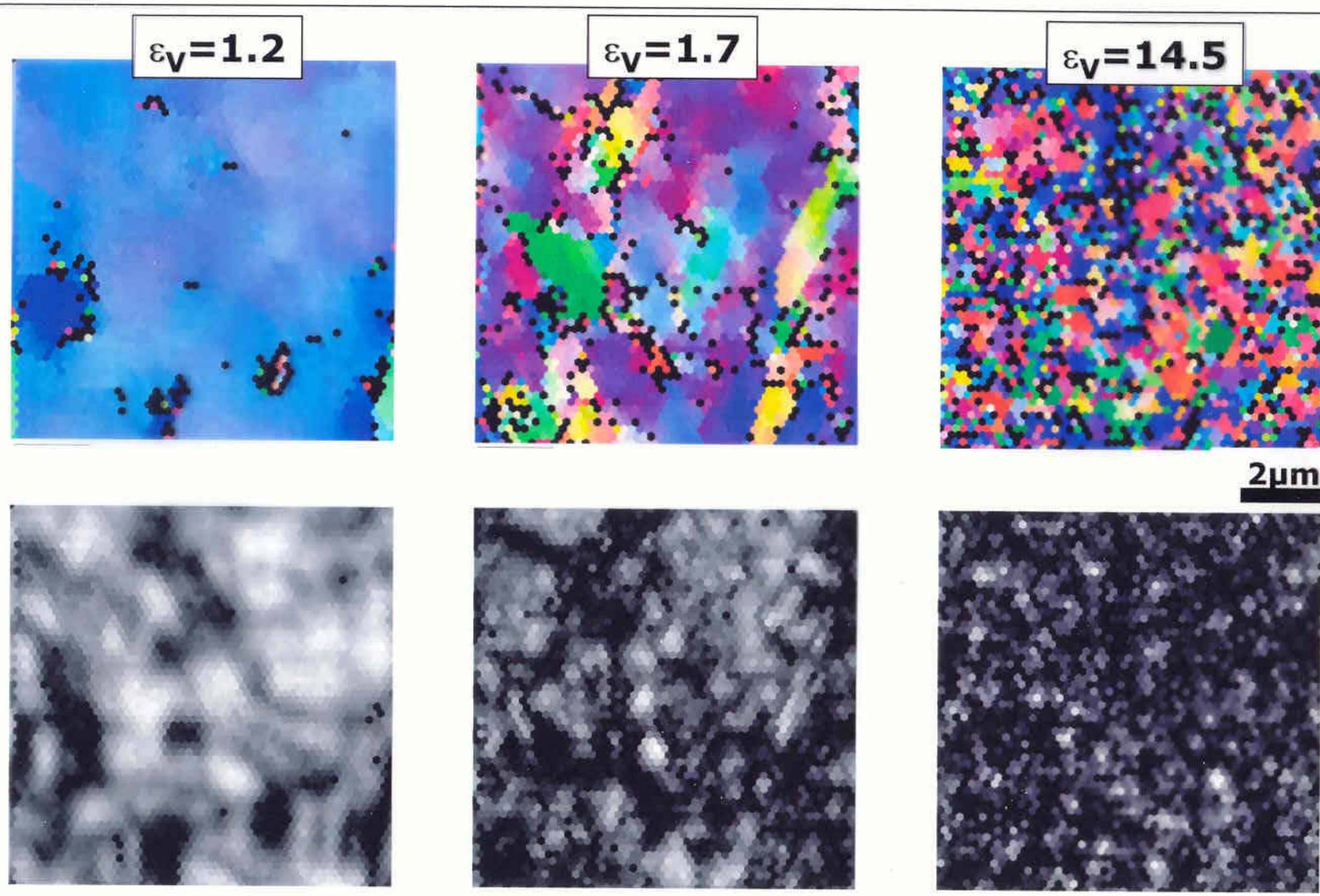
- Severe plastic deformation of metals leads to an extremely fine microstructure. This is produced by "fragmentation" of the original crystal structure. The mechanisms for this fragmentation are discussed. Various methods for severe plastic deformation are classified according to the strain paths involved:
  - ✓Continuous strain without change of strain path
  - ✓Accumulated strain without change of strain path
  - ✓Accumulated strain with reversal of strain path
  - ✓Accumulated strain with variable strain path
- For comparison of different experiments, the concepts of "equivalent strain" and "strain efficiency" are discussed.

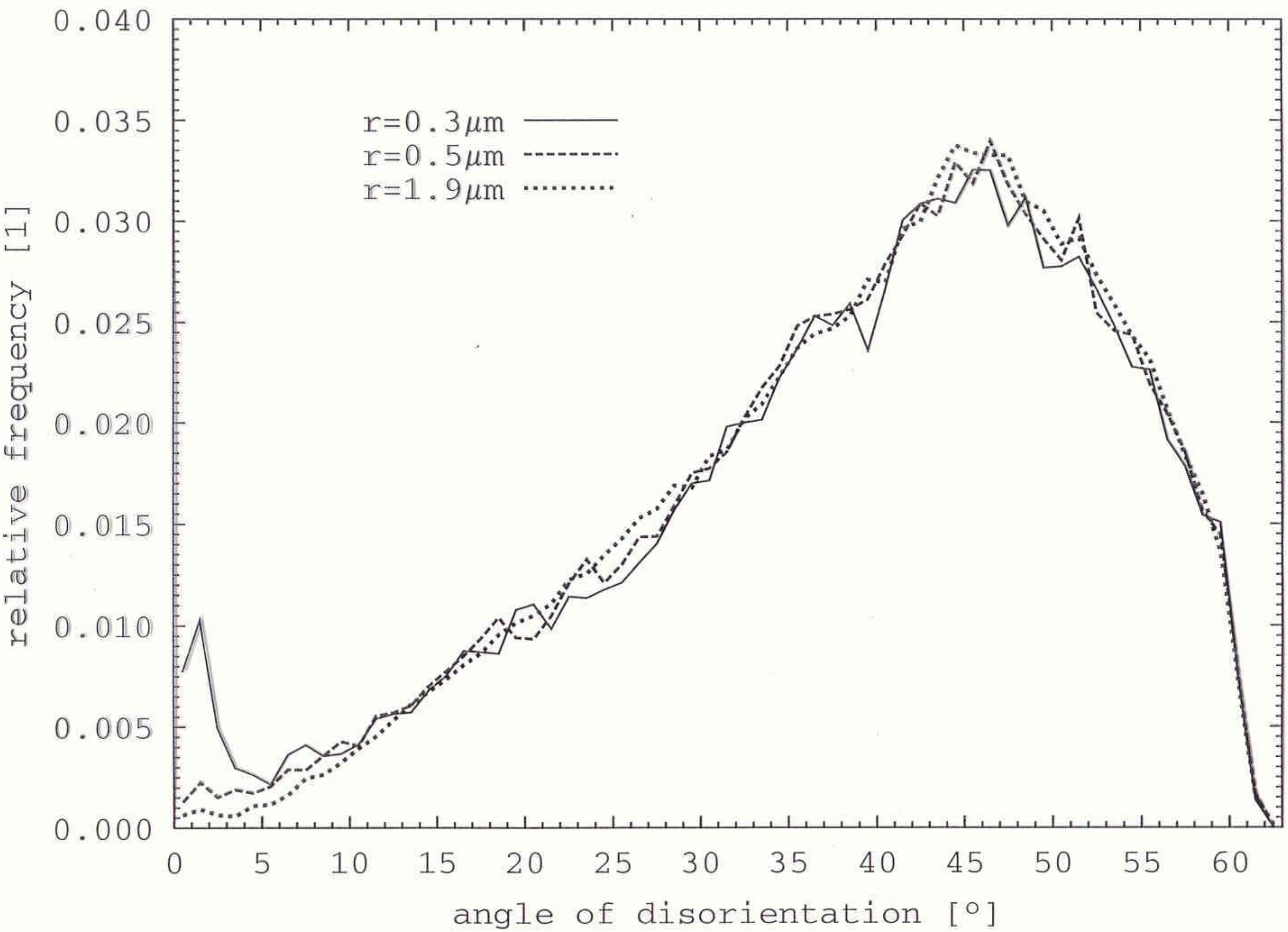
SPD

Continuous strain no change of strain path	Compression Extrusion Torsion (HPT)
Accumulated strain no change of strain path	Rolling Drawing ECA (route A) ?
Accumulated strain reversal of strain path	CEC ECA (route C) CCDC
Accumulated strain variable strain path	Swaging ECA (other routes) accumulated roll bonding

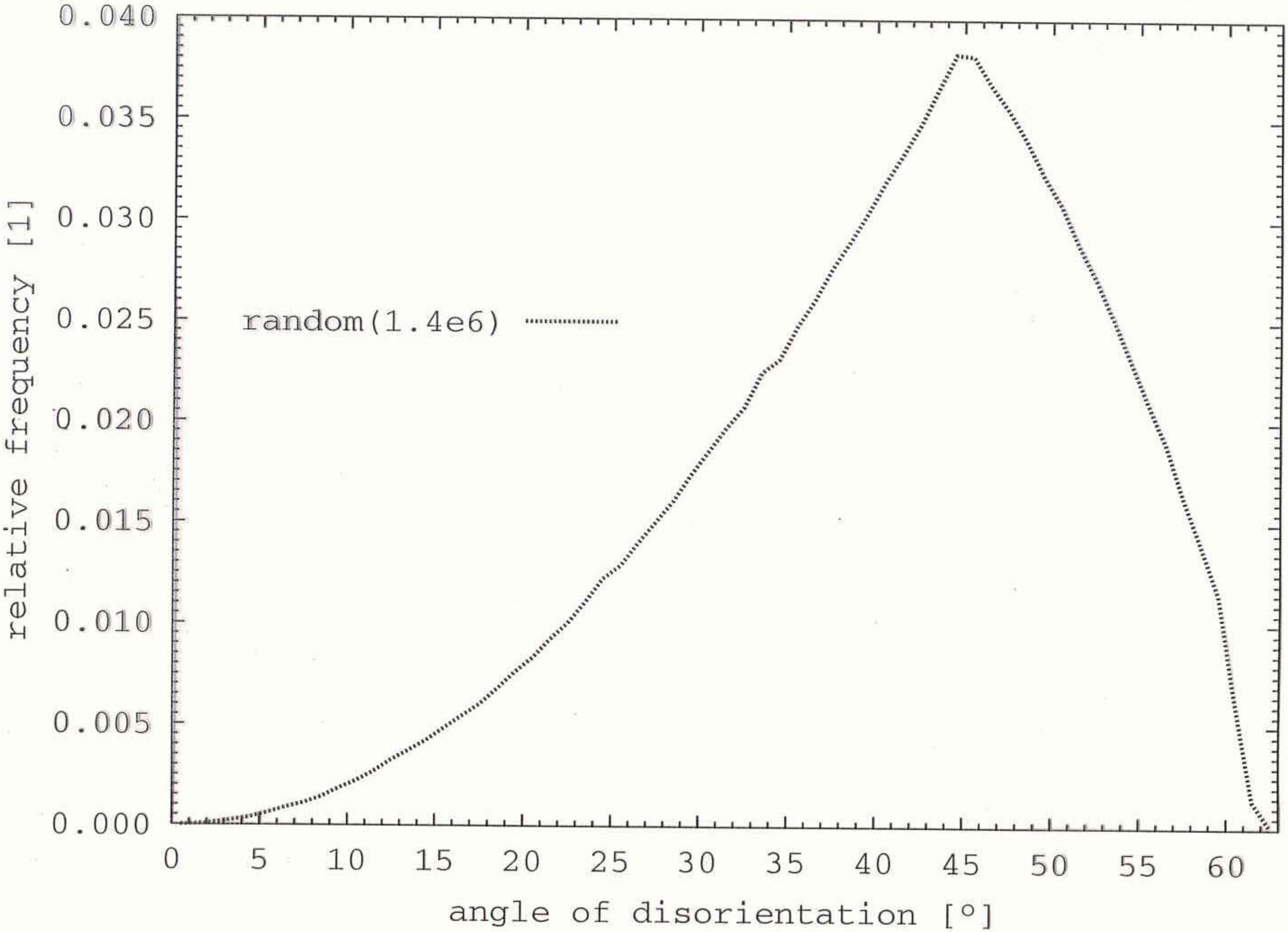
$\boxed{\text{equivalent strain ?}}$

evolution of microstructure at large strains in Cu

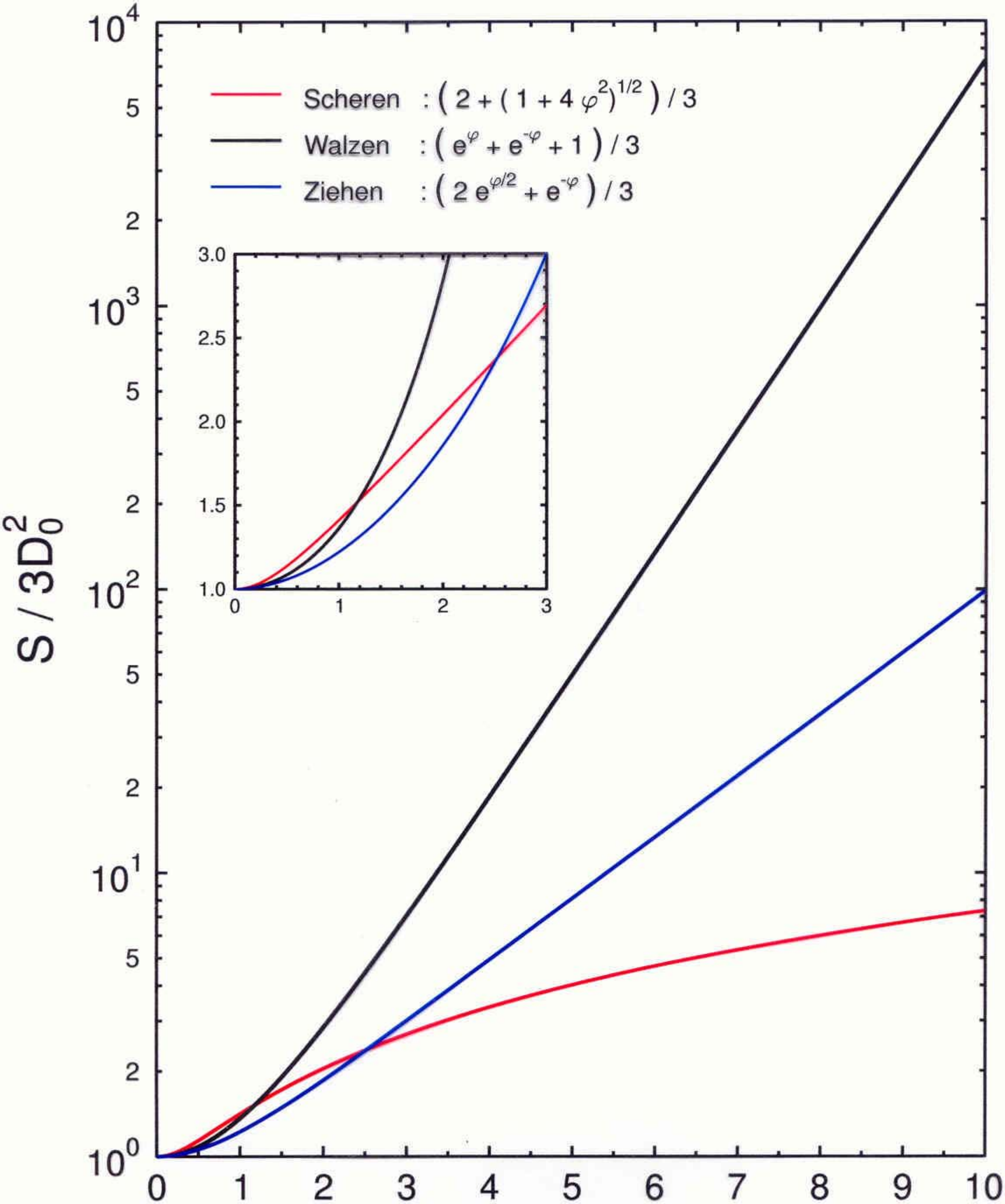




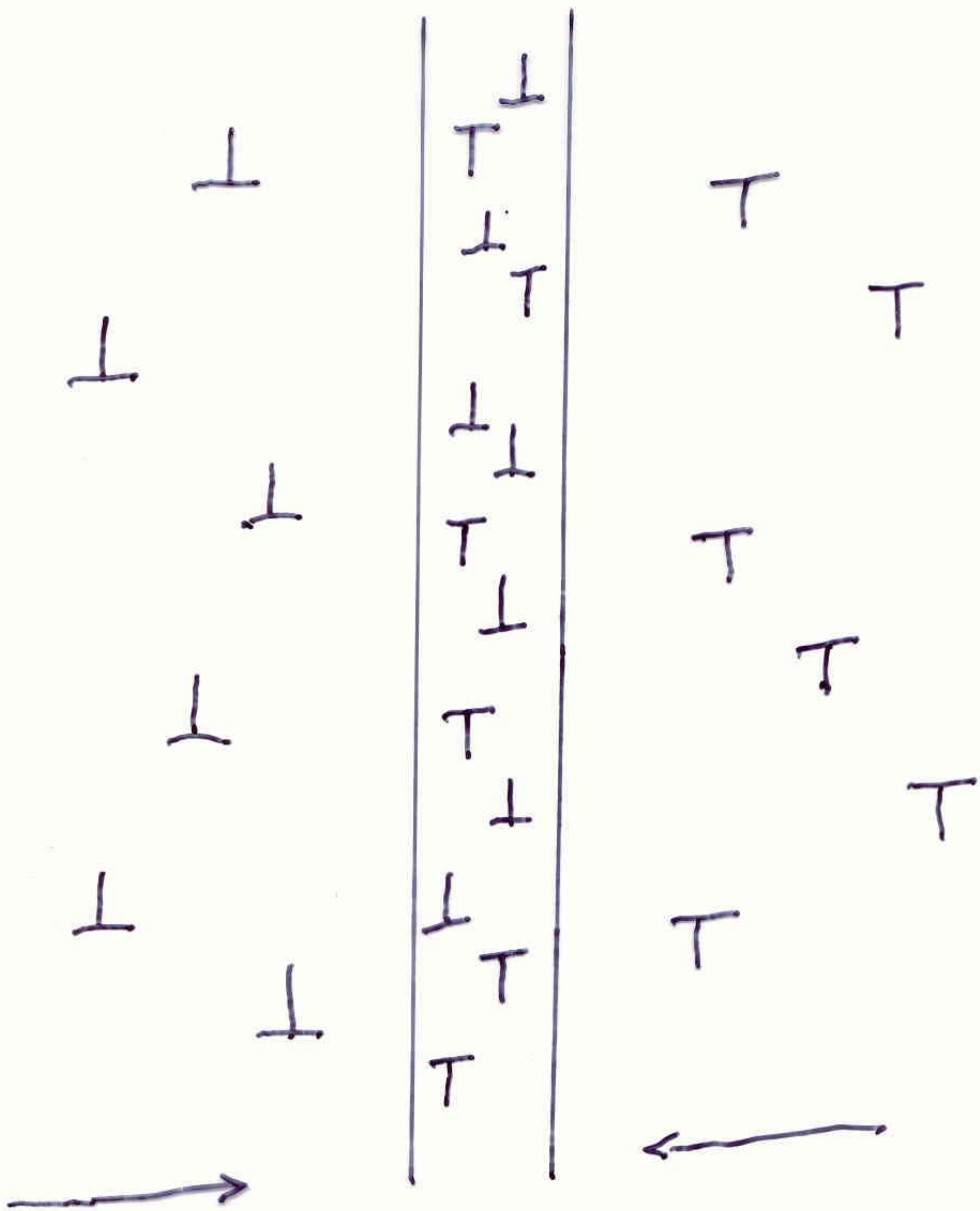
r=0.3μm
r=0.5μm
r=1.9μm
relative frequency [1]
angle of disorientation [°]
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0
5
10
15
20
25
30
35
40
45
50
55
60



0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
relative frequency [1]
random(1.4e6)
0
5
10
15
20
25
30
35
40
45
50
55
60
angle of disorientation [°]



Scheren : $(2 + (1 + 4\varphi^2)^{1/2})/3$
Walzen : $(e^{\varphi} + e^{-\varphi} + 1)/3$
Ziehen : $(2e^{\varphi/2} + e^{-\varphi})/3$
$S / 3D_0^2$
φ
10^0
10^1
10^2
10^3
10^4
0 1 2 3 4 5 6 7 8 9 10
1.0 1.5 2.0 2.5 3.0



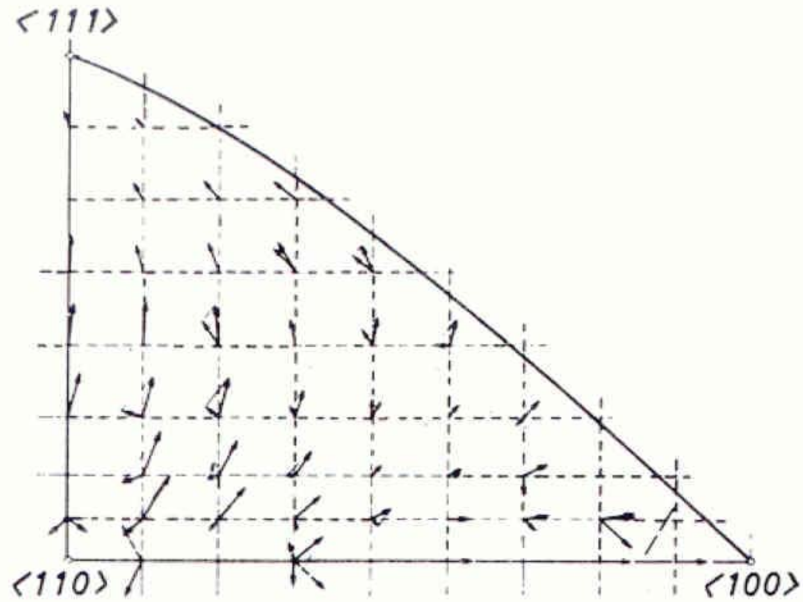
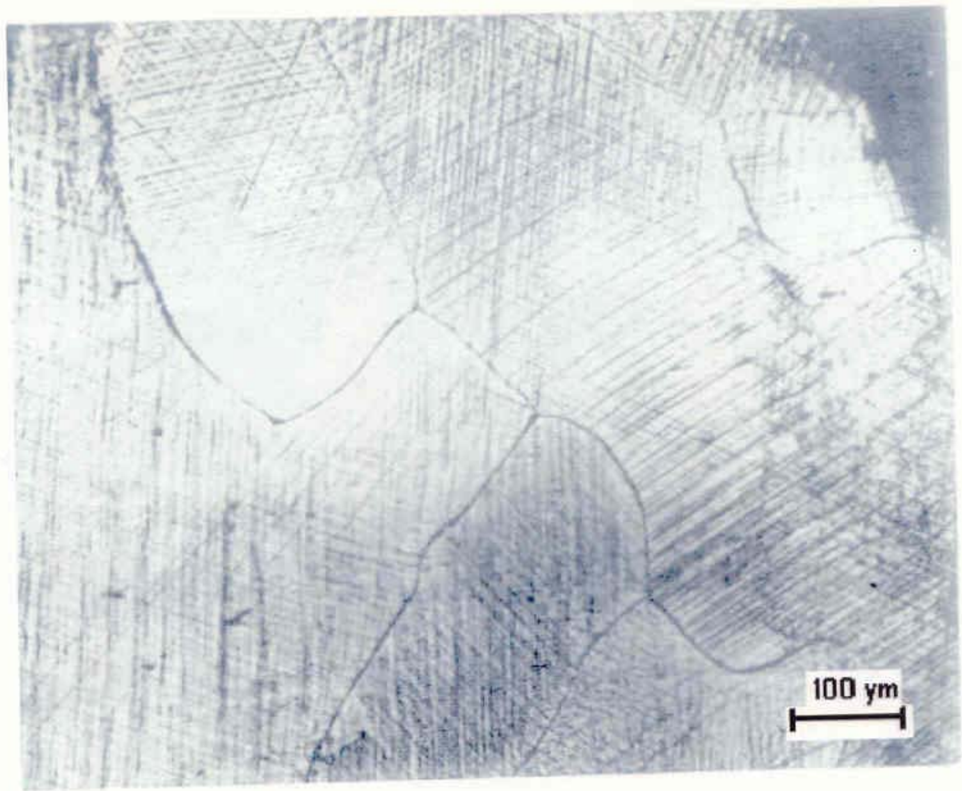
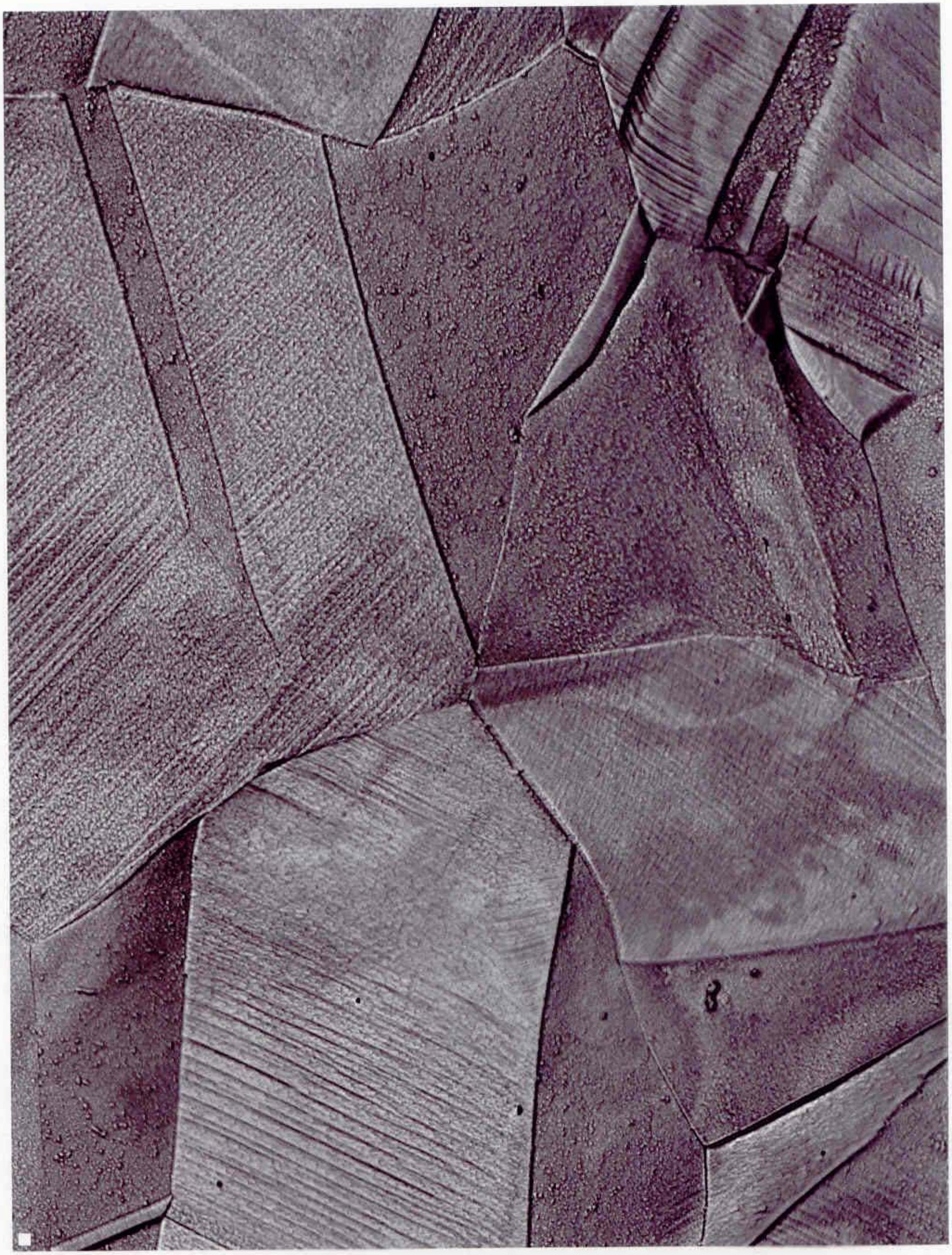


Fig. 1. Lattice rotations for axisymmetric tension, determined by TAYLOR [8] for {111}<110> slip. The sense of rotation is reversed for compression; 2.37% strain



Blei



Tension

$$\frac{A}{V} = \int \sigma \frac{dl}{l} = \int \sigma \, d\varphi$$

Simple Shear

$$\frac{A}{V} = \int \tau \, d\gamma$$

Equivalent Strain for

$$\int \sigma \, d\varphi = \int \tau \, d\gamma$$

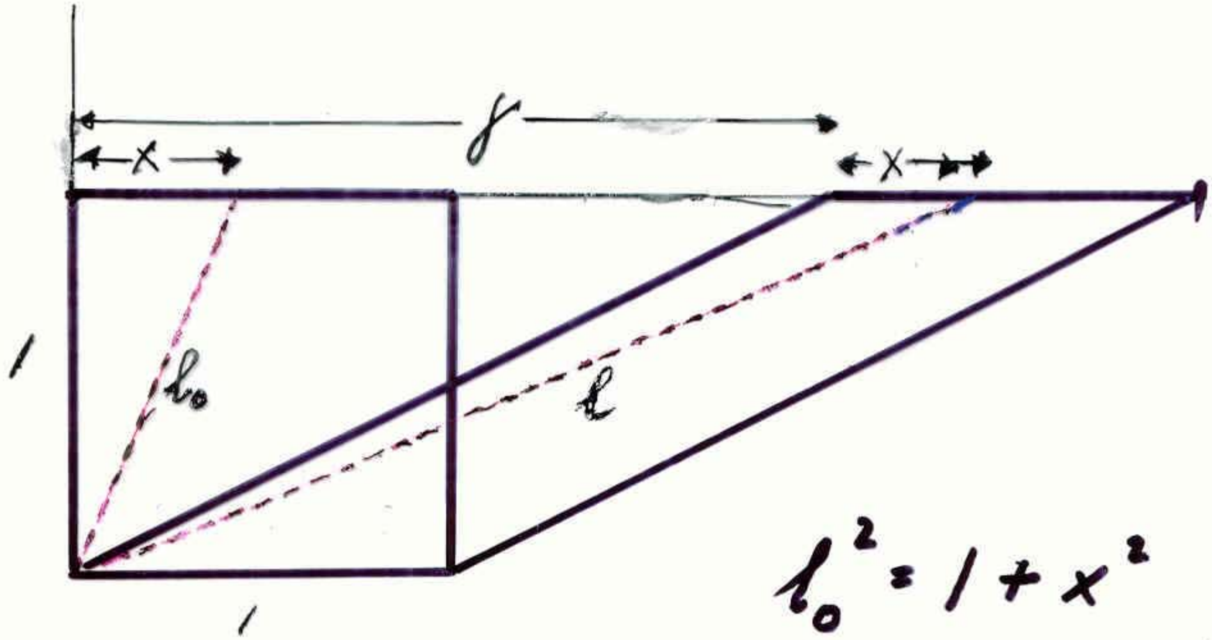
fulfilled for

$\sigma = a\tau$ and $d\varphi = \frac{1}{a} d\gamma$

$\downarrow$ $\downarrow$

Tresca : $a = 2$?

v. Mises : $a = \sqrt{3}$



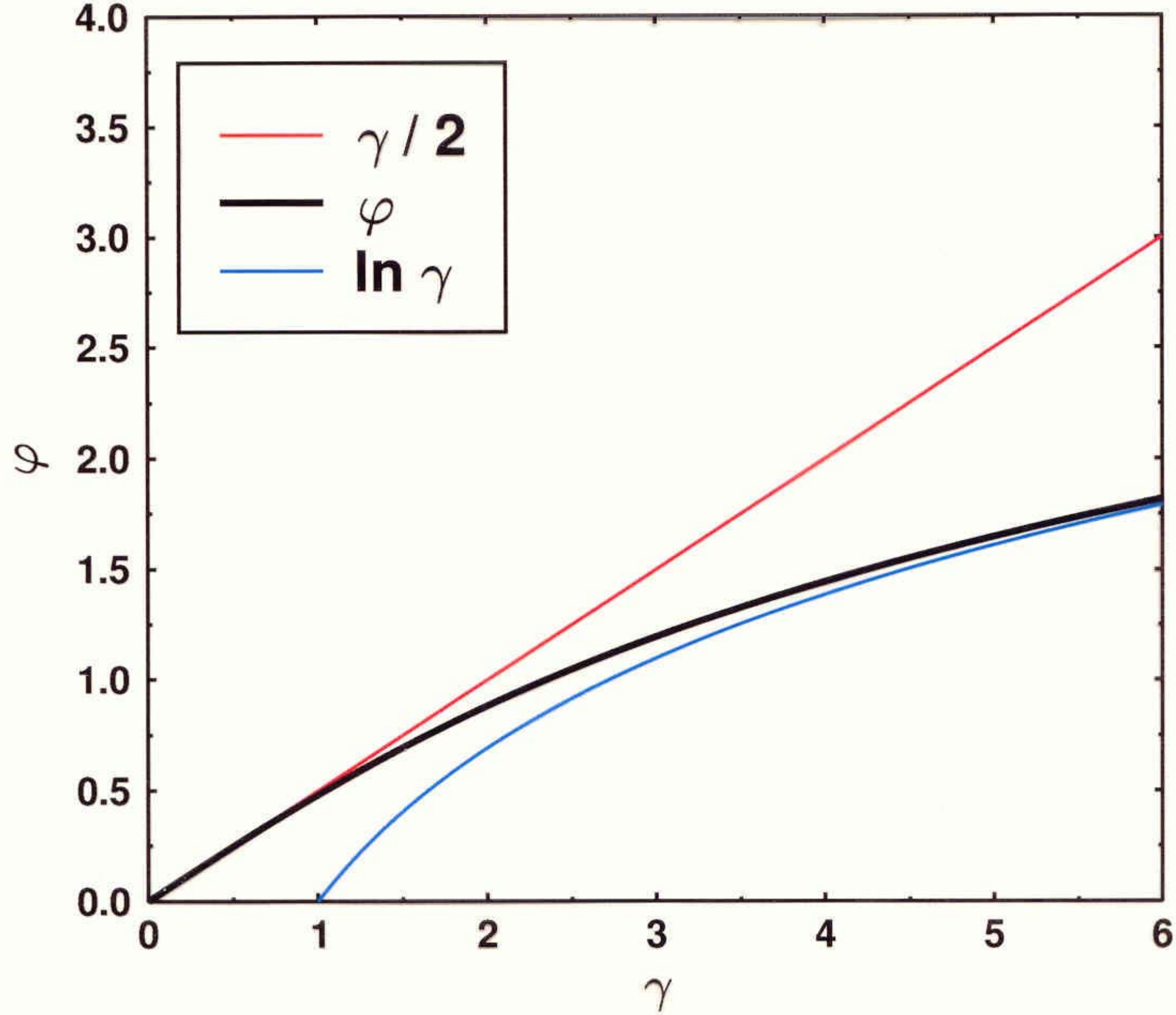
$$\ell_0^2 = 1 + x^2$$

$$\ell^2 = 1 + (\gamma + x)^2$$

$$\frac{d}{dx}\left(\frac{\ell}{\ell_0}\right)^2 = 0 \rightarrow \quad x = \sqrt{\frac{\gamma^2}{4} + 1} - \frac{\gamma}{2}$$

$$\varphi = \ln \frac{\ell}{\ell_0}$$

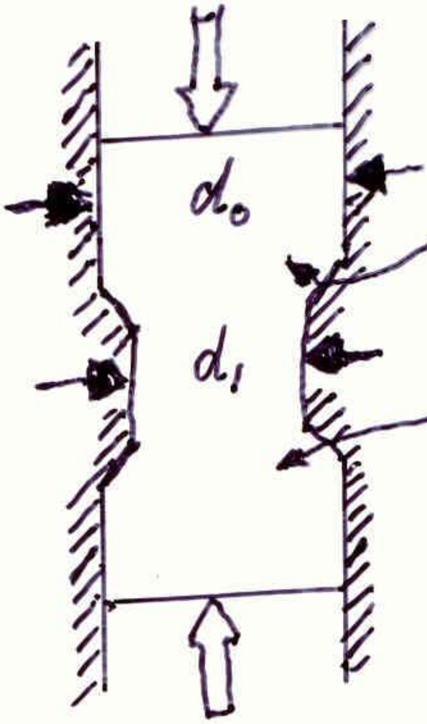
$$\ln \frac{\ell}{\ell_0} = \frac{1}{2} \ln \frac{1 + \left(\sqrt{\frac{\gamma^2}{4} + 1} + \frac{\gamma}{2}\right)^2}{1 + \left(\sqrt{\frac{\gamma^2}{4} + 1} - \frac{\gamma}{2}\right)^2}$$



4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
$\gamma / 2$
φ
$\ln \gamma$
φ
γ

Reversal of strain path

CEC



$$\Delta\varphi_1 = \ln\left(\frac{d_0}{d_1}\right)^2$$

$$\Delta\varphi_2 = -\Delta\varphi_1$$

$$\varphi_{equ} = \sum_{1}^{2n} |\Delta\varphi_n| \quad ?$$

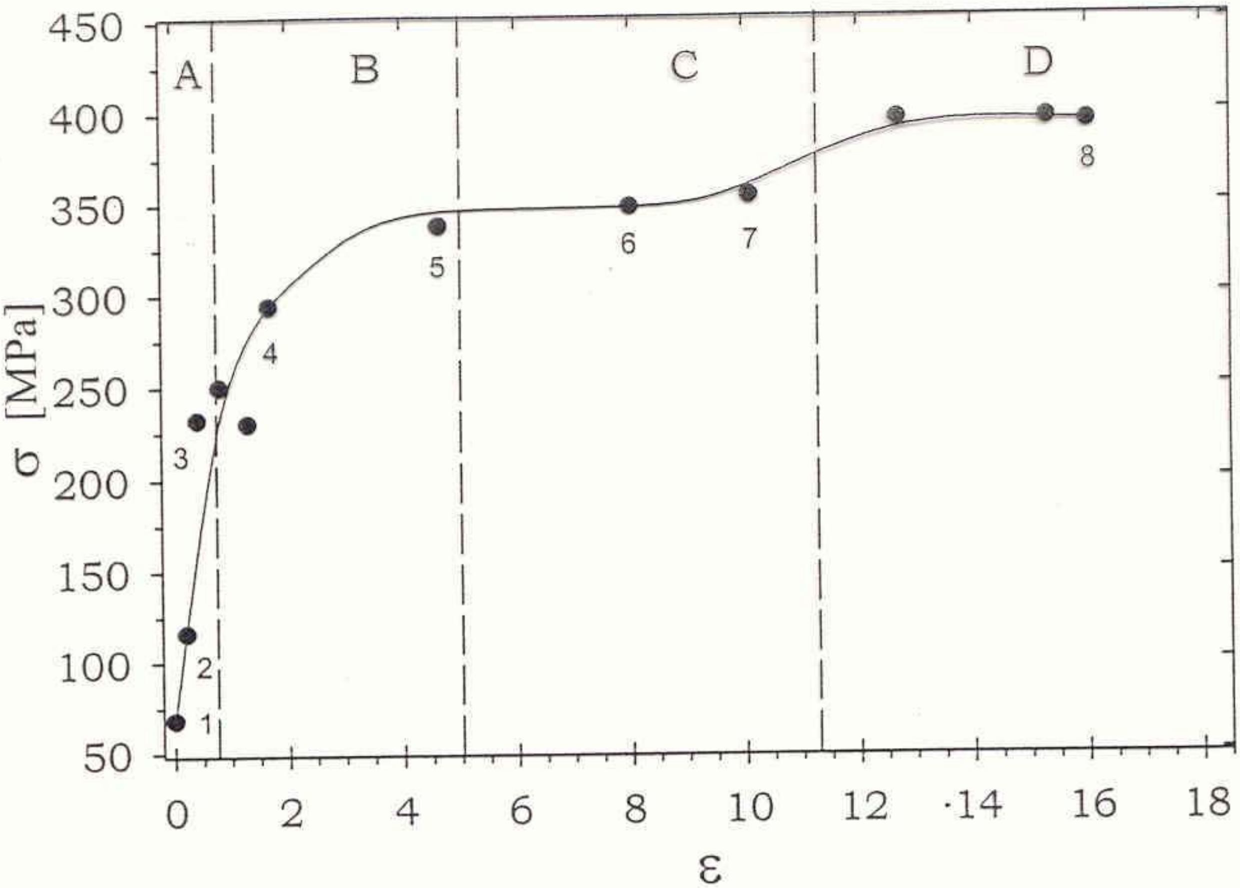
$$\varphi_{equ} = \eta \sum_{1}^{2n} |\Delta\varphi_n|$$

$$\frac{d\rho}{d\gamma} \approx \frac{2M}{\Lambda b} \text{ — recovery } \begin{cases} \text{dynamic} \\ \text{"geometric"} \end{cases}$$

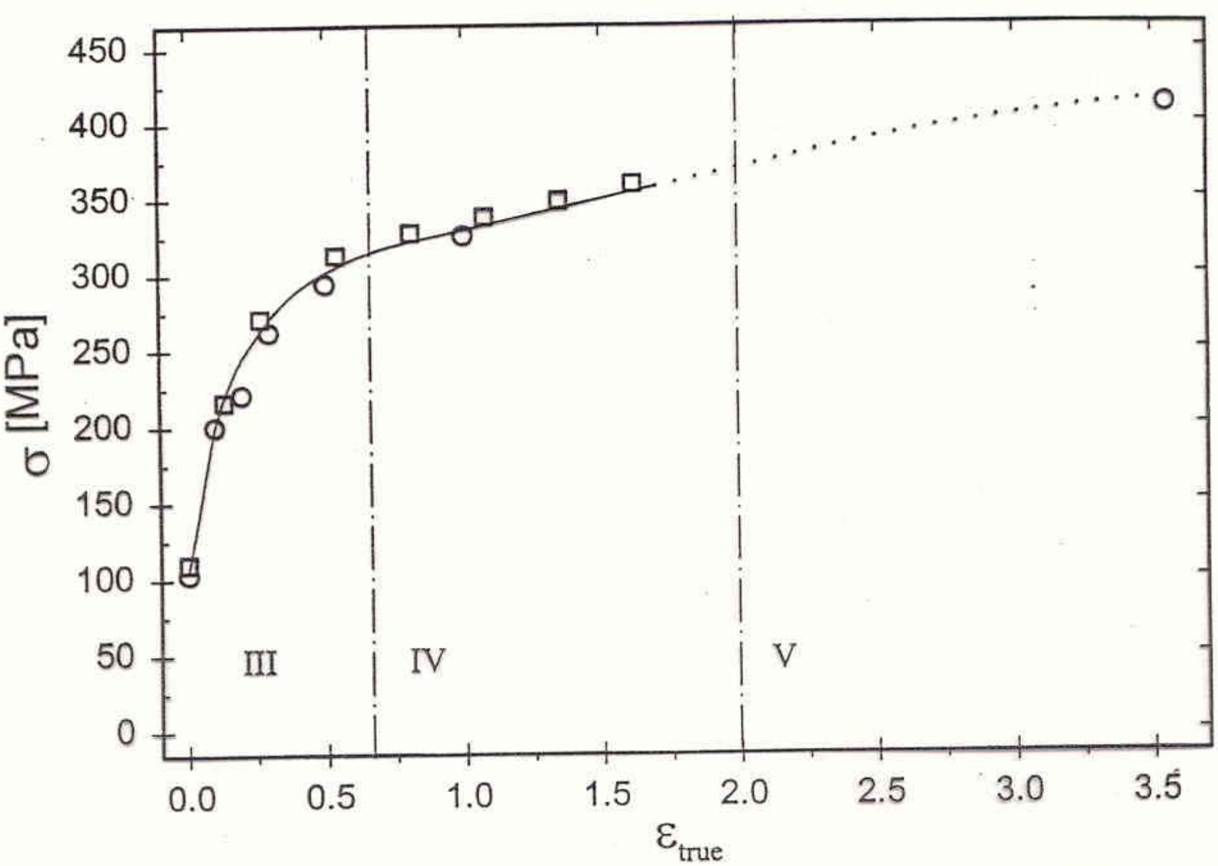
$$\gamma = 2\varphi \rightarrow a = \frac{d\gamma}{d\varphi} = 2$$

$$\gamma = e^{\varphi} \rightarrow a = \frac{d\gamma}{d\varphi} = \gamma$$

AlMg5

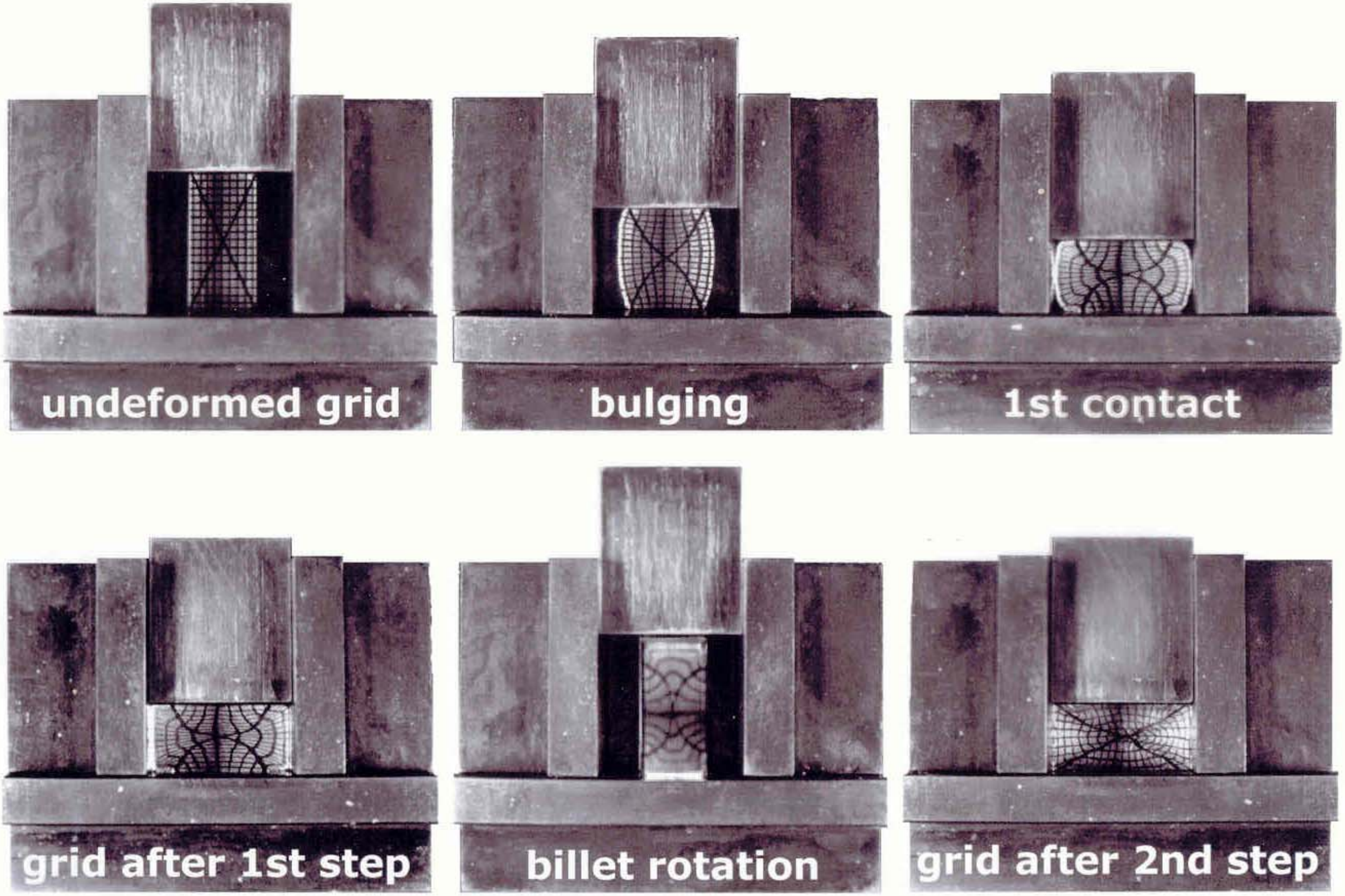


CEC $\varepsilon = \Sigma|\Delta\varepsilon|$

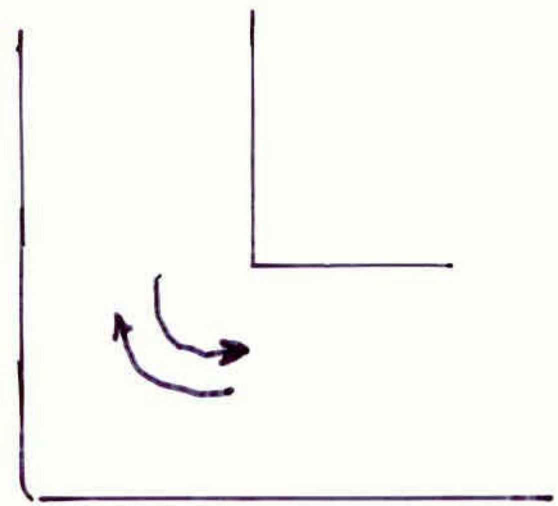


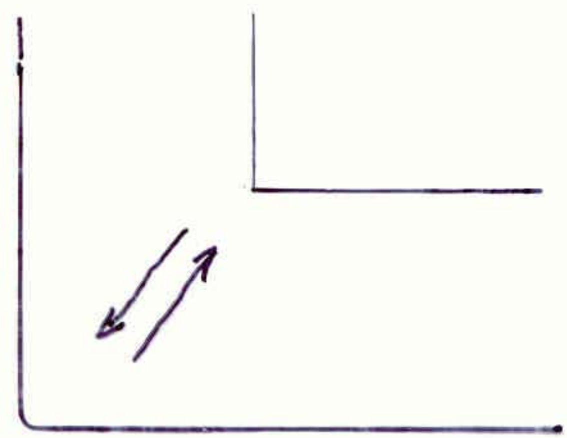
unidirectional strain

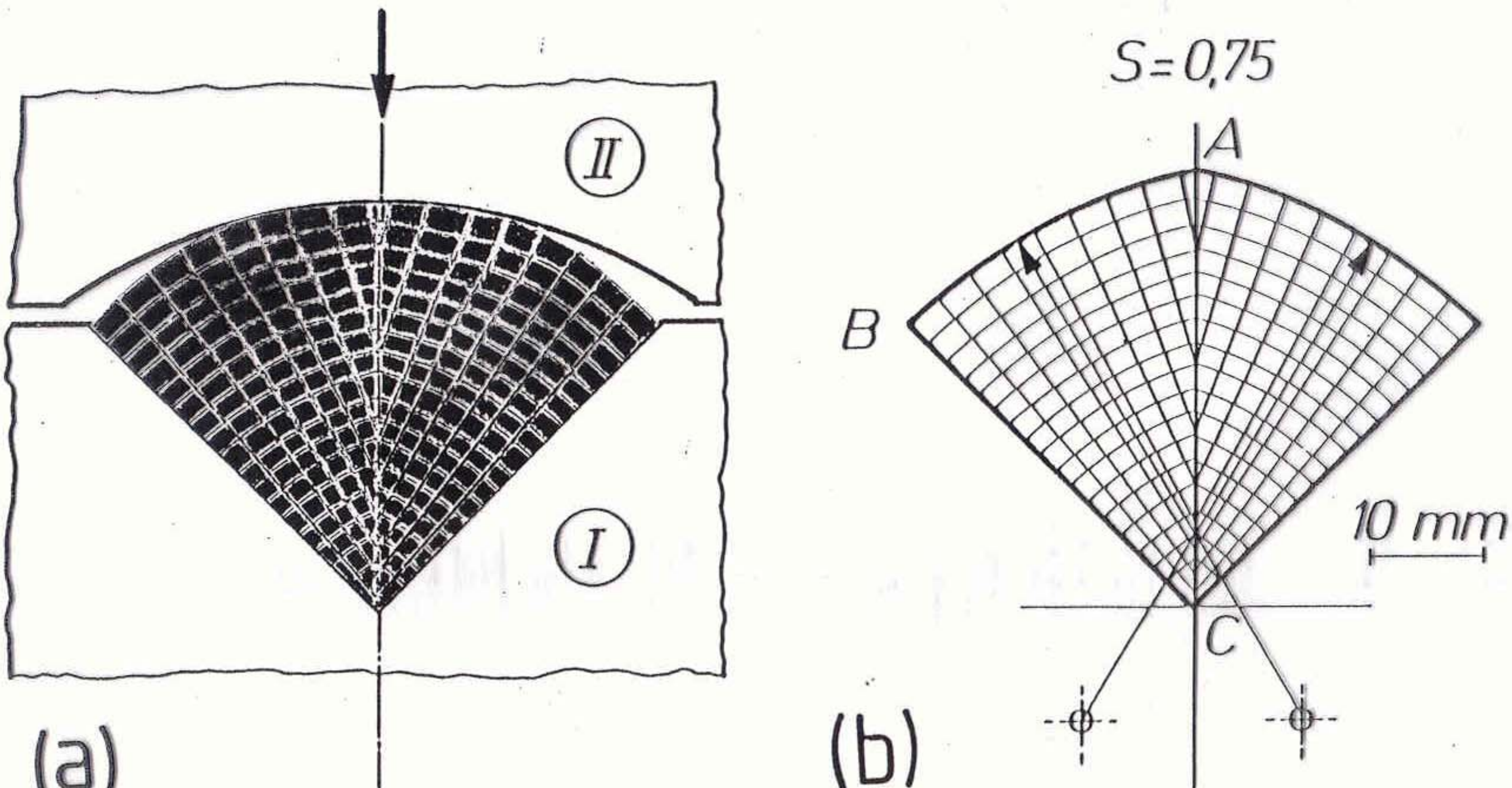
Cyclic Channel Die Compression (CCDC)



ECA

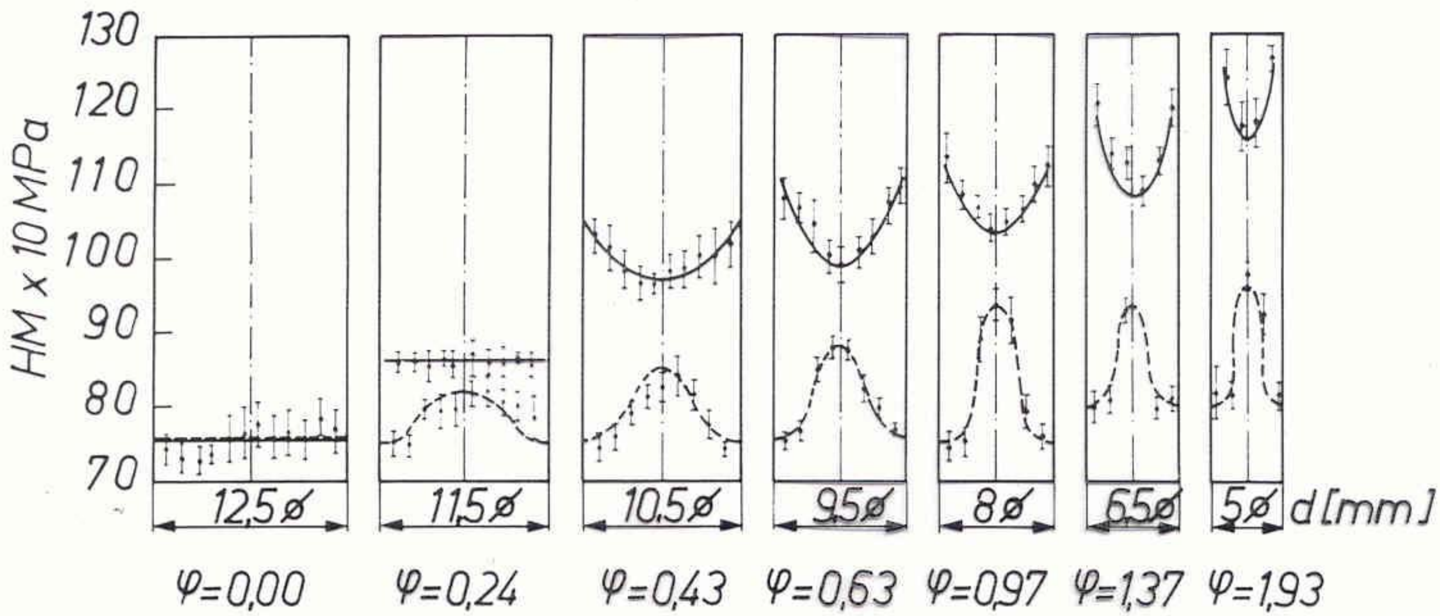






a distorted grid after partial deformation; b lead testpiece with scratched-in polar coordinate grid

4 Visioplastic experiment



HM x 10 MPa
130
120
110
100
90
80
70
12,5 ∅
11,5 ∅
10,5 ∅
9,5 ∅
8 ∅
6,5 ∅
5 ∅
d [mm]
φ=0,00
φ=0,24
φ=0,43
φ=0,63
φ=0,97
φ=1,37
φ=1,93

CONCLUSIONS

- SPD produces microstructures with very small structural elements separated by interfaces built up of many dislocations produced by straining. The process of fragmentation is discussed.
- For a comparison of the efficiency of different SPD techniques to produce such structures the traditional concept of “equivalent strain” based on equal mechanical work is problematic, especially when strain is accumulated in steps with varying strain path where “geometric recovery” must be taken into account.